

A New Scheme for High-Intensity Laser-Driven Electron Acceleration in a Plasma

A. A. Rukhadze,^{1, a)} S. P. Sadykova,^{2, b)} T. G. Samkharadze,² and P. Gibbon²

¹⁾*Prokhorov General Physics Institute, Russian Academy of Sciences, Vavilov Str., 38., Moscow, 119991, Russia*

²⁾*Forschungszentrum Jülich, Jülich Supercomputing Center, Jülich, Germany*

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We propose a new approach to high-intensity laser-driven electron acceleration in a plasma. Here, we demonstrate that a plasma wave generated by a stimulated forward-scattering of an incident laser pulse can be in a longest acceleration phase with an incident laser wave. This is why the plasma wave has the maximum amplification coefficient which is determined by the breakdown (overturn) electric field in which the acceleration of injected relativistic beam electrons occurs. We estimate qualitatively the acceleration parameters of relativistic electrons in the field of a plasma wave generated at the stimulated forward scattering of a high-intensity laser pulse in a plasma.

Keywords: High-intensity laser-driven plasma wakefield acceleration, Ultrarelativistic electron bunch, Laser-Plasma interaction, Stimulated forward-scattering

During the past few decades plasma accelerators have attracted increasing interest of scientists from all over the world due to its compactness, much cheaper construction costs compared to those for conventional one and various applications ranging from high energy physics to medical and industrial applications. An intense electromagnetic pulse can create a plasma oscillations through the stimulated scattering. Electrons trapped in the plasma wave can be accelerated to high energy.

The idea to accelerate the charged particles in a plasma medium using collective plasma wave fields generated by the high-energy electron beams belongs to the Soviet physicists G. I. Budker, V. I. Veksler and Ia. B. Fainberg¹⁻³ in 1956, whereas assumptions for generation of plasma Langmuir waves by nonrelativistic electron bunches propagating through plasma were first made earlier in 1949^{4,5}. High-energy bunch electrons generate a plasma wave in such a way that the energy from a bunch of electrons is transferred to the plasma wave through stimulated Cherenkov resonance radiation producing high acceleration electric fields. Later on, another acceleration scheme using a laser⁶ or time-shifted sequence of bunched high-energy electrons injected into a cold plasma was proposed⁷. In recent experiments at the Stanford Linear Accelerator Center it was shown that an energy gain of more than 42 GeV was achieved in a meter long plasma wakefield accelerator, driven by a 42 GeV electron beam⁸. For a detailed review about the modern status of this research field we would like to refer a reader to^{9,10}.

However, the experiments of the 60s and 70s demonstrated that efficiency of acceleration using the high-energy beams is much less than the expected one and the generated field is much lower than a breakdown (over-

turn) electric field¹¹:

$$E_{pmax} = 2\pi m V_p \omega_p / e. \quad (1)$$

where e - electron charge, m - its mass, V_p - plasma wave phase velocity, $V_p = \omega_p / k_p \simeq c$ where k_p - plasma wave vector, ω_p - plasma frequency, $\omega_p = \sqrt{4\pi e^2 n_e / m}$ with n_e being the electron density and m - its mass. The explanation for the experiments failure was given in the work¹² where it was shown that trapping of electrons in a generated by a beam plasma wave occurs and as a result growth of the field amplitude stops when the field amplitude is much less than that of the breakdown field^{13,14}.

With the appearance of the high-intensity lasers in the 80s, a new era of plasma acceleration has begun. The hopes were feeded by possibility of the stimulated scattering of a laser pulse by plasma electrons in a rare plasma with the generation of high-intensity longitudinal plasma wave where the electron trapping does not occur and, as a result, high fields with respect to the breakdown field E_{pmax} can be generated. However, there are still a lot of unsolved problems related to the development of instabilities hindering the laser-driven plasma-based acceleration¹⁰.

We presume that the key issue of the laser-driven plasma-based acceleration is the following: inspite of the fact that the instability induced by the backward (backwards the laser pulse) scattering generating a plasma wave or a wake has a maximum increment δ_1 compared to that generated by a forward (towards the injection of a laser pulse) one δ_2 by $\sim 2\omega_0 / \omega_p$ times (ω_0 - laser pulse frequency)¹³ (see Fig. 1), this acceleration scheme is not suitable for particle acceleration because such lasers have a very short laser pulse length. Since the wave vector of a plasma wave \vec{k}_p is equal to the double magnitude of that of a laser pulse ($k_p \simeq 2\omega_0 / c$), the phase velocity of a plasma wave is quite low. Due to this fact the wave leaves behind both the laser and the back scattered

^{a)}Electronic mail: rukh@fpl.gpi.ru

^{b)}Electronic mail: Corresponding author - s.sadykova@fz-juelich.de

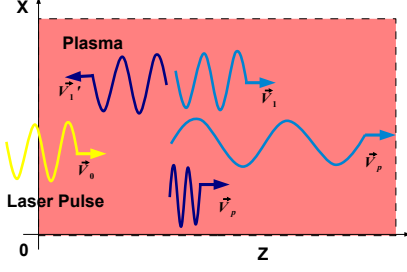


FIG. 1. Schematic 2D-illustration of interaction of the high-intensity laser pulse with plasma which generates the plasma wave and forward- and backward-scattered waves with $|\vec{V}_p| = |\vec{V}_0| = |\vec{V}_1|$, $k_0 \simeq k_1 > k_p$ (forward-scattered wave), V_1' - backward-scattered wave, where $|k_0| \simeq |-k_1| < |k_p|$.

waves getting localized at the back to the front of the laser pulse (this is why it is called as a wake). As a result the plasma wave gets soon out of the acceleration phase with the laser wave and the electron beam injected into the plasma gets soon out of a phase with the plasma wave what halts the acceleration process. In the range of carried out experiments the acceleration efficiency estimates to not higher than 20-50 %. Recently, the SPARC_LAB facility of INFN-LNF in Frascati, Italy, reported the observation of electrons acceleration with an energy gain of 420 MeV (300 %) out of 150 MeV injected using a 250 TW laser system ($\lambda = 800$ nm, $\tau = 25$ fs, $E_M = 6$ J)¹⁵ (see Fig. 2).

In this work, we are first to propose another acceleration scheme, namely: a stimulated forward-scattering based plasma acceleration. In addition, on a base of such model we would like to give some explanations for the experiment¹⁵. Due to the stimulated laser forward-scattering a plasma wave is generated as well. In this case, the plasma wave and laser wave can stay in acceleration resonance for a much longer time.

Let the laser pulse with Langmuir frequency ω_0 be injected into the cold plasma at $\omega_0^2 \gg \omega_p^2$. Consider the case when $Z||\vec{V}_0, \vec{V}_1$ and \vec{V}_p - phase velocities of laser, forward-scattered and plasma waves. Here, we employ the CGS system of units. The parametric resonance for the stimulated forward-scattering can be written as following:

$$\begin{aligned}\omega_0 &= \omega_1 + \omega_p \\ k_0 &= k_1 + k_p,\end{aligned}\quad (2)$$

where k_0 , k_1 and k_p are the wave vectors of the incident laser pulse, forward-scattered wave and plasma wave respectively, ω_0 , ω_1 - corresponding frequencies:

$$\begin{aligned}\omega_0 &= \sqrt{\omega_p^2 + k_0^2 c^2} \\ \omega_1 &= \sqrt{\omega_p^2 + k_1^2 c^2},\end{aligned}\quad (3)$$

After having solved the system of Eqs. (2) and (3) one

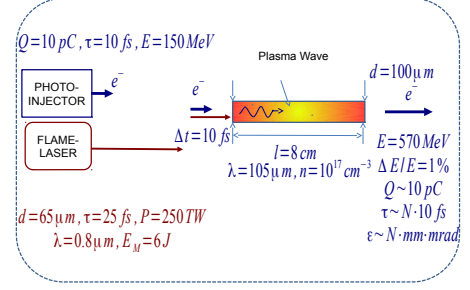


FIG. 2. Schematic drawing of the experiment made at the SPARC_LAB facility of INFN-LNF in Frascati, Italy¹⁵.

can find out that the phase velocities of three waves are equal

$$\left(V_0 = \frac{\omega_0}{k_0}\right) = \left(V_1 = \frac{\omega_1}{k_1}\right) = \left(V_p = \frac{\omega_p}{k_p}\right) = c \left(1 + \frac{\omega_p^2}{2\omega_0^2}\right), \quad (4)$$

where $\omega_p^2/\omega_0^2 \ll 1$. The condition for the resonance interaction (4) can be satisfied for a sufficiently long time until the amplitude of the plasma wave becomes higher than that of the laser incident wave and the reversed process of feeding back the incident wave starts. If the laser is powerful enough than the instability will keep growing until a breakdown (overturn) of the plasma wave occurs, i.e. when the magnitude of the saturation plasma wave amplitude becomes equal to E_{pmax} (see Eq. 2). The acceleration constraint (1) enables us to control the acceleration process. In order to determine the electron trapping condition for acceleration we need to estimate the duration of acceleration, i.e. the time interval during which the phase velocities of a plasma wave and that of an electron remain approximately equal to each other. This condition possibly was taken into account during the SPARC_LAB experiment in Frascati with injected electron beam energies of 150 MeV.

Taking into account this condition we can estimate the duration of acceleration of an ultrarelativistic electron with an initial energy $\varepsilon = mc^2(\gamma - 1)$, $\gamma = 1/\sqrt{1 - u_0^2/c^2} \gg 1$, u_0 is the speed of an electron beam. The speed of such an electron is the following:

$$\frac{u_0}{c} = 1 - \frac{1}{2\gamma^2} \quad (5)$$

Using the following estimation formula for acceleration time:

$$(V_p - u_0)\tau_f \simeq c\pi/\omega_p. \quad (6)$$

and Eqs. (4) and (5) we can determine the acceleration time :

$$\tau_f \approx \frac{2\pi\gamma^2\omega_0^2}{\omega_p(\omega_p^2\gamma^2 + \omega_0^2)}. \quad (7)$$

Taking into account Eq. (1) and (7) the following momentum and energy growth can be obtained:

$$\Delta P \approx eE_{pmax}\tau, \quad \Delta\varepsilon \approx eE_{pmax}\tau c. \quad (8)$$

Let us make some estimations for a laser-driven plasma-based electron accelerator and compare with the results obtained at the SPARC_LAB facility of INFN-LNF in Frascati, Italy.

• Estimated parameters

- $\omega_0 = 2.35 \cdot 10^{15} \text{ s}^{-1}$ ($\lambda = 800 \text{ nm}$), $\omega_p = 1.8 \cdot 10^{13} \text{ s}^{-1}$, $n_e = 10^{17} \text{ cm}^{-3}$
- An electron with energy growth of 150 MeV ($\gamma = 297$) can gain the maximum energy $\Delta\varepsilon \simeq 0.3 \cdot 10^{12} \text{ eV}$ in the saturation field of $E_{pmax} \simeq 1.9 \cdot 10^9 \text{ V/cm}$ during $\tau_f = 5 \cdot 10^{-9} \text{ s}$ over the maximum acceleration length of $L \simeq 150 \text{ cm}$. Provided that the length of a capillary could be of the same size: $L \simeq 150 \text{ cm}$, the corresponding energy growth for the SPARC_LAB facility can be estimated to much higher energy growth of $\Delta\varepsilon \simeq 15 \cdot 10^9 \text{ eV}$ compared to the obtained one.
- The acceleration time in a frame of the stimulated back-scattered model can be determined as $\tau_b = \pi/\omega_p$, $\tau_b \simeq 10^{-13} \text{ s}$ which is much less than that for the forward-scattered case: $\tau_f \simeq 10^{-9} \text{ s}$ by approx. γ^2 times (provided that $\gamma \gg \omega_0/\omega_p$). The corresponding plasma wave lengths will be $\lambda_b = \pi c/\omega_0$, $\lambda_b \simeq 0.5 \mu\text{m}$ and $\lambda_f = 2\pi c/\omega_p$, $\lambda_f = 105 \mu\text{m}$.

I. RESULTS AND DISCUSSIONS

In the present work for the first time the analytical problem of interaction of a high-intensity laser pulse with plasmas in a frame of a stimulated forward-scattering model has been solved and a new approach to solution of the problem was proposed.

The acceleration scheme employing the stimulated backward-scattered wave for particle acceleration in a wakefield is not suitable for particle acceleration because high-intensity lasers have a very short laser pulse length leading to a very short interaction time between the injected electron beam and plasma wave. Instead, our new approach employing the stimulated forward-scattering

can provide more durable particle trapping time inside the field of a plasma wave of a much longer length compared to the back-scattered model where electrons just slip off the wave. In Eq. for a breakdown electric field for illustration purpose we took a constant top field because the exact electric field profile during the instability growth is not known. However, the time interval during which the breakdown field can be gained is much less than the acceleration time what justifies our choice of the field profile. For a better and detailed research we are planning to run more extensive simulations of the considered phenomena using the **KARAT** code¹⁶.

In order to acquire the maximum acceleration efficiency during the experiment one would need to make the scattered at various angles radiation except the forward-scattered one be absorbed by plasma surrounding surfaces similar to the scheme employed for a SHF (super-high frequency) plasma amplifier.

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